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PHOTOGRAPHIC MEASUREMENTS OF DAYLIGHT IN DEEP WATER

BY

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T photo-electric measurement of submine daylight on board the »Albatross» was gerally not extended to greater depths than 2(m even in the clearest oceanic water. By us g a sensitive galvanometer, *e. g.* an *Ising* ga anometer, which is mounted for work at se and gives a sensitivity of $4 \cdot 10^{-10}$ aperes per scale-unit, it is possible to go fu her down to about 300 m. Considering th an amplification of the weak photocurents is rather complicated, this depth m/ be the practical limit for photo-electric dermination of daylight in the sea. For st deeper water a photographic method offers itself as most suitable.

Photographic methods were used in some of he first attempts to study subsurface light. In 1885 Fol and Sarasin exposed photographic plates at different depths in the Mediterranean off Cote d'Azur. Here, they found faint residual daylight still observable at 400 m depth.

Some exposures were made in 1910 in the vinity of the Azores by Helland-Hansen (12). Using panchromatic plates exposed in the water directly to daylight, he found at 5(m a considerable illumination that was obviously higher on a horizontal than on a vertical surface. Even at 1000 m there was a blackening on his plate.

In 1911 Bertel (1911) photographed in the Mediterranean the daylight spectrum by means of a spectrograph and determined how far down the different wave-lengths gave blackening of the plate.

In the uppermost waterlayers Knudsen (1922) and later on Erikson (1933) employed accurate spectro-photographical methods giving a quantitative spectral analysis of the light at every level.

With the aid of a camera designed for work in deep water we have tried to make a quantitative study of daylight from 100 m down to 500. The measurements have been limited to two areas, the waters between the Marquesan Islands and Tahiti, and the Sargasso Sea and its surroundings. The former area is interesting in view of the problem of submarine light and the growth of coral reefs, whereas the Sargasso Sea with its wellknown brilliant blue colour is supposed to be the clearest natural water in the world.

The photo-electric measurements of submarine daylight are the subject of another report (Vol. III. No. 1). Some of the results are introduced into the following discussion in order to give a complete picture of the decrease in daylight with increasing depth.

Deep-sea Camera

This is constructed according to the following chief principles. A photographic camera without lenses is used to record the illumination on an opal glass exposed to daylight in the water. The camera shutter is operated by means of a watch so that different exposure times can be pre-selected. Camera and watch are mounted inside a container capable of withstanding a pressure of 100 atmospheres (Figs. 1 and 2).

The container is cast in two pieces of light

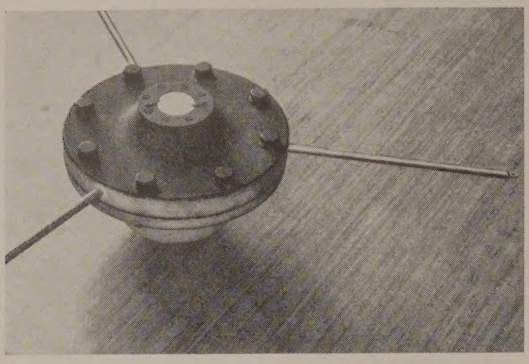

Fig. 1. The deep-sea camera . . .

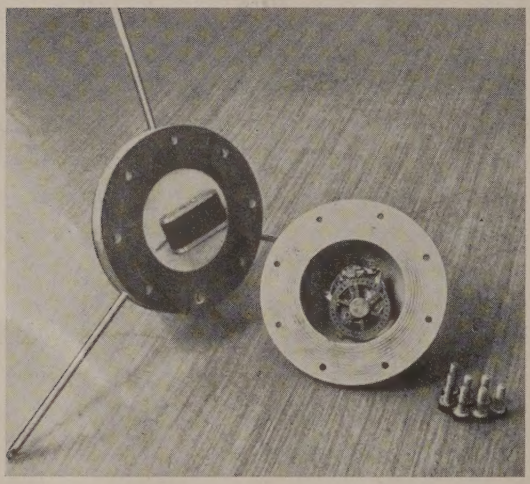

Fig. 2. . . . and taken apart.

metal (Hiduminium RR 53 C—4). It is anode-oxidized in order to reduce corrosion. The peripheral part of the circular top plate is 30 mm thick, increasing to 60 mm at the centre, where the window is mounted, so as to reduce incurvation (Fig. 3). The window *W* (Pyrex Brand glass from Corning Glass Works) is 25 mm thick and 60 mm in diameter. It is clamped between fairly hard rubber rings, leaving 33 mm of the glass unsupported. An opal glass *O* is placed at the top, flush with the rim surrounding it. The lower part of the container is hemispherical and 15 mm thick, with a flange 20 mm. The watch *K* is placed inside the half sphere, whereas the camera *A* is screwed to the top plate.

The camera is a Tenax camera (24×24 m without lenses provided with a comu shutter. It permits the making of expo of 1/300, 1/100, 1/10, 1/5, 1/2, 1 second, on time.

The watch (Westerstrand & Söner), wi has a strong spring, acts on a release to wi the shutter is hooked (Fig. 4). The releas well as the watch made for this purpos similar to the standard type but of a he construction. The watch can be so adj that after an optional time the shutt pressed, making a short-time exposure opening the camera for a long exposure the latter case, after an interval of time 5 minutes to 3 hours, the shutter is rele and the camera closes.

The deep-sea camera is suspended from wire of the hydrographical winch. The d is timed so that the exposure is made sh after the camera reaches the desired dept is important to avoid obliquity of the and to keep the camera at the fixed d Sometimes, a pair of reversing thermom

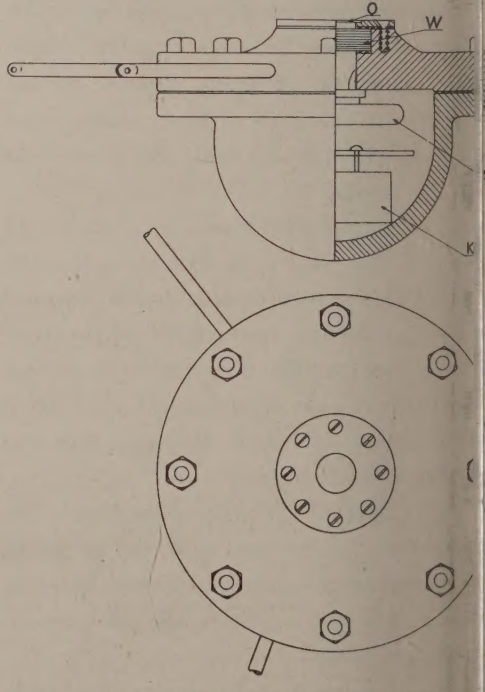

Fig. 3. Plan of the deep-sea camera.

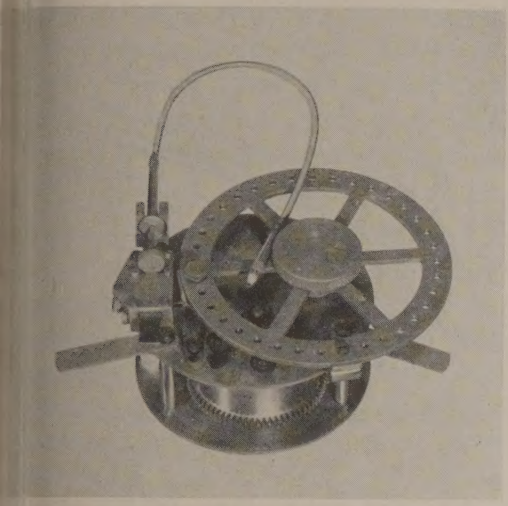

Fig. 4. The watch and release.

consisting of one protected and one unprotected thermometer was placed 2 m above the camera in order to determine the depth. During exposure the daylight above the sea was always recorded.

Photometric Procedure

The daylight spectrum at 100 m in the clearest oceanic water has a width at half maximum height of about from 420 to 500 mμ. It narrows with increasing depth and therefore a film-material is required that shows little variation in sensitivity within the assigned limits. We have found Kodak Plus X suitable, but later on we also used Kryptar film.

Calibration exposures of the film were made in the laboratory in close approximation to the field conditions. They should preferably be made for the same intensities as are met with the depth interval studied, *i. e.* 100—500 m. As the daylight is reduced roughly from 1 to 10^{-9}, this demand could not be completely fulfilled. In all, we took 11 calibration exposures on every film, using three different intensities and varying the exposure time from 1 second to 1000 seconds.

Another important fact is the spectral distribution of the calibration light. This must be similar to the residual daylight below 100 m. The spectral response to the daylight is well attained by using, in connection with an ordinary projection lamp, two Corning filter glasses, *viz.* Yellow Green No. 4014 with a thickness of 1.4 mm, and Heat Resisting Lantern Blue No. 5543 with a thickness of 5.2 mm. The former filter cuts off the spectrum towards short wave-lengths at 430 mμ, the latter filter towards long wave-lengths at 520 mμ. The final light distribution including that of the lamp, for which the colour temperature is known, has its maximum at about 480 mμ.

Fig. 5 shows the device constructed for the calibration. L is a projection lamp of 110 volts, kept at 2.00 amperes, C is a condenser, A the camera, F colour filters, and D a disc. The disc contains screens with different absorption power, which are brought into the light beam by rotating the disc. The reduction factors are determined by means of a photoelectric cell. The selective effect of the screens on the narrow spectral block is negligible.

In the first experiment we had to find out proper exposure times. In Table 1 there is a collation of exposure times selected for different depths. The first film was developed to a low gamma (0.5—0.6) in order to cover a wide range of densities. Later we could work with a higher gamma (0.9) affording greater accuracy. The ordinary Kodak developer D 76 was used at a temperature of 19 centigrade.

The next step is to evaluate the blackening on every exposure. It is clear from the photo-

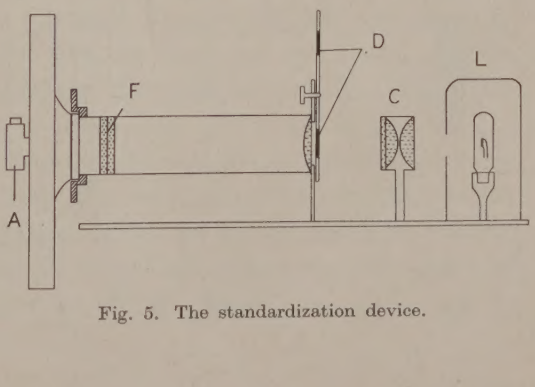

Fig. 5. The standardization device.

gram in Fig. 6 that the blackening is of uniform density within a circle of six mm. This enabled us to use on board a simple photometer (Figs. 7 and 8), in which a light beam three mm in diameter is transmitted through the film (F) and impinges on a photo-electric cell (E). This is connected with the *Ising* galvanometer, and the photo-current reading will give a measure of the blackening.

The submarine light intensities are derived in the following way. The density is defined

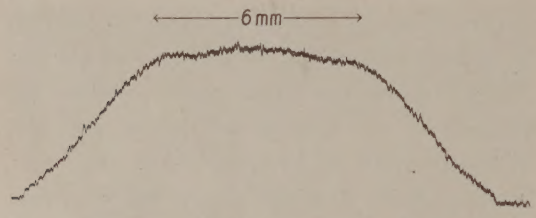

Fig. 6. Photogram showing the uniform density of the blackening within a circle of 6 mm.

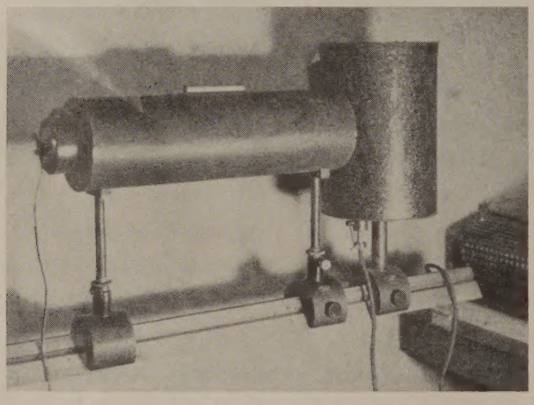

Fig. 7. The photometer for evaluating the blackening of the film.

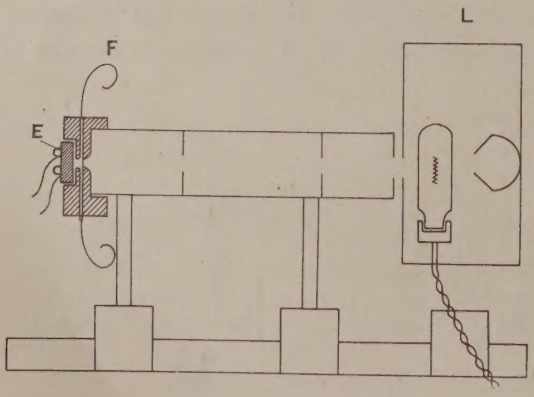

Fig. 8. Plan of the photometer (Fig. 7).

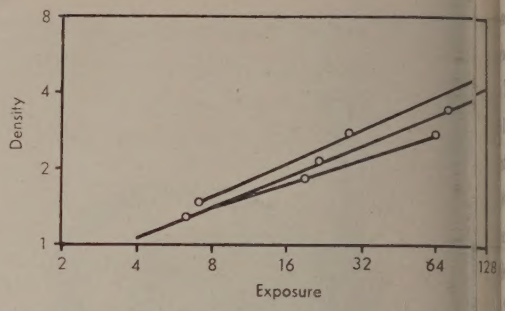

Fig. 9. Relation between density and exposure for Kodak Plus X, 35 mm film. The straight lines connect exposure values for the same exposure time.

TABLE 1. Suitable exposure times of Kodak Plus X at different depths.

Depth m	Exposure time
100	$1/100^s$
200	1^s
300	1^m
400	20^m
500	2^h

as the logarithm of the ratio of the intensity transmitted through the back-ground on the film to that transmitted through the actual spot. The logarithm of computed density is plotted against the logarithm of the exposure which produced it at the calibration. Exposure values should preferably be on the straight part of the obtained characteristic curves, but too dense negatives are avoided, as they are not evaluable with accuracy. If exposure values for the same exposure time (Fig. 9), or if exposure values for the same light intensity are connected, two sets of characteristic curves are obtained. By interpolation between these, in some cases, by extrapolation the desired exposures are found. If the exposure time *in situ* is known the corresponding daylight intensity will come out in relative units.

Results

The results from six stations are shown in Table 2, three of them in the area between Marquesas and Tahiti (Stations 98, 99, 101), and three in, or near, the Sargasso

(S tions 365, 373, and 376). The percentage of urface light is computed for the various le s. The deep-sea camera has not been used ab e 100 m, but the extinction of the most pe trating blue light was studied between 0 an 100 m by means of photo-electric methods. Fo each experiment the observed mean solar alt ude is given. The last two columns in Ta e 2 contain the computed vertical extinc- tio coefficients and the percentage of light tra smitted through 100 m. Extinction coeff- ici ts are often made more comparable if re ced to zenith sun. This may be useful for the upper layers but serves no purpose for deep water. It is true that the directional ch acter of submarine daylight is slowly lost, bu at great depths, where a limiting angular dis ibution is approached, this must be very lit affected by solar altitude. In the South Se the exposures could be made at nearly zenith sun but in the Atlantic most measure- me ts were carried out at lower sun: conse- qu tly these latter transmissions should be so ewhat increased, in any case at small and mo erate depths, in order to be comparable wi the others.

he water in the South Sea is very uniform as to transparency, whereas at a typical Sa asso station (Station 373) the intensity of da ight is reduced much less in the upper stra a than further down. The high trans- pa ncy of the first 100 m in the Sargasso Sea is onfirmed by two photo-electric measure- me ts in the blue — 465 mμ (Stations 372 an 374), given for comparison in Table 3. It ay be mentioned that these experimental re ults agree well with a theory for the sub- ma ne daylight proposed by LE GRAND (1939) an concerning pure water at moderate depths. As o the surface problems, the discussion of thi is contained in the report on the photo- el ric work.

he content of particles studied by the Tyndall method is lower in the upper strata of he South Sea than in those of the Sargasso Sea, whereas further down a slight though not decisive trend in the opposite direction is noticeable. Values of the residual daylight in deep water are a little higher for the former than for the latter area, even if due regard is taken to the difference in solar altitude. Thus the highest intensity of daylight in deep water was observed at Station 101.

Coming with the »Albatross» from the south-east and approaching the Antilles we observed that surface water of intense blue colour alternated with sharply bordered regions of greenish-blue water. The low transmission between 0 and 100 m at Station 365 appears in a water of the latter type and is attributed to a fairly high content of dissolved matter and of particles. The origin of this water may be the turbid areas off the coast of South America. CLARKE (1941), who has studied light penetration in the south-western section of the North Atlantic Ocean, states that a sudden drop in transparency is encountered at N 11°, W 56°. Between 100 and 400 m at Station 365 the transmission is not far from that found for the Sargasso Sea, so the deep water is not in any high degree contaminated. Likewise, when leaving the Sargasso Sea on a ENE route we found the optical properties of the upper strata to change rapidly. Already at Station 376 (Table 2) and the adjacent Station 377 (Table 3) the high transmission is absent. On the other hand, the deep water shows a very small change in transparency. In fact, the water below 100 m, as far as it has been investigated in these areas of the Atlantic, is remarkably uniform in this respect. At Station 376 an exposure was tried at 500 m. The exposure time was two hours, and the computed intensity amounts to 10^{-9} of the surface intensity. This may be the practical limit for the use of the deep-sea camera. During his descent in the ocean off Bermuda BEEBE (1934) observed that complete darkness for the human eye was reached at a depth of between 520 and 580 m.

TABLE 2. Percentages of surface light (470 mμ) and vertical extinction coefficients, determined by the deep-sea camera.

Station	Position		Date	Solar altitude	Depth m	Percentage of surface light	Vertical extinction coefficient	Transmission through 100 m
	Latitude	Longitude						
			1947					
98	S 13° 03′	W 146° 01′	Oct. 21		0	100		
				85°	100	3.0	0.035	3.0
				87°	200	$1.1 \cdot 10^{-1}$	0.033	3.6
99	S 14° 12′	W 147° 37′	22		0	100		
				85°	300	$4.3 \cdot 10^{-3}$	0.033	3.5
101	S 15° 57′	W 148° 57′	23		0	100		
				77°	100	3.4	0.034	3.4
				78°	400	$1.2 \cdot 10^{-4}$	0.033	3.5
			1948					
365	N 14° 32′	W 55° 05′	August 5		0	100		
				85°	100	1.2	0.044	1.2
				85°	400	$5.7 \cdot 10^{-6}$	0.041	1.7
373	N 28° 25′	W 61° 05′	24		0	100		
				68°	100	5.7	0.029	5.7
				60°	400	$4.2 \cdot 10^{-5}$	0.039	2.0
376	N 30° 29′	W 56° 07′	27		0	100		
				65°	400	$4.6 \cdot 10^{-6}$	0.042	1.5
				45°	500	$1.0 \cdot 10^{-7}$	0.038	2.2

TABLE 3. Vertical extinction coefficients (465 mμ) from photo-electric measurements.

Station	Position		Date 1948	Solar altitude	Depth range m	Vertical extinction coefficient	Transmission through 100 m
	Latitude	Longitude					
372	N 24° 32′	W 63° 19′	August 21	64°	0—100	0.028	5.8
				64°	100—200	0.043	1.3
374	N 28° 33′	W 59° 49′	25	68°	0—100	0.029	5.5
				68°	100—200	0.041	1.6
377	N 30° 38′	W 56° 05′	28	70°	0—100	0.039	2.1
				69°	100—200	0.043	1.4

The results from Stations 101, 373, and 376 appear in Fig. 10 and demonstrate the straightness of the logarithmic plots for deep strata.

The question of the change of the angular distribution with increase of depth and of the equilibrium that is approached in deep water is fully discussed in the photo-electric report. As a contribution to highly needed data from great depths we made an attempt also to study with the aid of the camera the horizontal component of daylight. As the horizontal nd the vertical intensity could not be rec ed simultaneously, it was, when measuring, st essential to keep the wire vertical in ord to be sure of the desired depth. The camera as suspended from the wire at only one o its arms so as to rotate in the water during he exposure with the camera axis horizo al. In consequence, the obtained value of he horizontal component constitutes a mean ue

for different azimuths. As everything argues in favour of its change with azimuth being small at 400 m, the total horizontal component H defined by ATKINS and POOLE (1940) can be derived by multiplying with π the intensity found through the exposures to horizontal light.

In Table 4 a few results are listed for comparison of H and V. At Station 375 two exposures to the horizontal light were carried out at 400 m, but the corresponding exposure to the vertical light unfortunately did not succeed before the sun had become covered by dense clouds. In this case the value of V is computed by interpolation between measurements at Station 373 and 376 and cannot be credited with the same accuracy as other values. The ratio H/V for Station 375 is, therefore, disregarded in taking the average. Corresponding values of H and V were not obtained at exactly the same solar altitude. The mean path-length for daylight in the upper layers is dependent on the solar altitude. In deep water, however, it is irrespective of the conditions above the sea surface. The values in Table 4 are only for the first 100 m reduced to the same path length. This may seem a bit arbitrary but is of no importance, as the corrections decrease H/V for Station 373 and increase H/V for Station 376, so that the average is very much the same whether corrections are employed or not.

TABLE 4. The ratio of the horizontal to the downward illumination H/V, determined by the deep-sea camera.

	Position		Date 1948	Depth m	H/V %
	Latitude	Longitude			
3	N 28° 25′	W 61° 05′	August 24	400	69
5	N 29° 21′	W 58° 09′	26	400	(69)
6	N 30° 29′	W 56° 07′	27	400	53

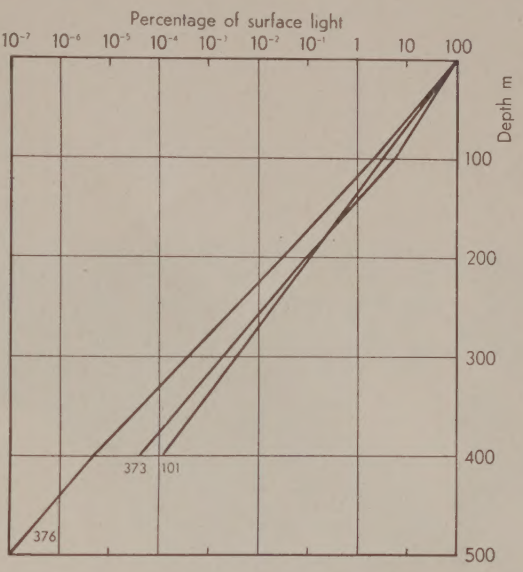

Fig. 10. Percentage of surface light at different depths at Stations 101, 373, and 376.

Hence the results of these exposures indicate that at 400 m

$$H/V = 60\ \%$$

This result may be compared with data from the upper strata. Photo-electric measurements extended to 175 m have revealed that H/V is not much higher than 60 %. In view of this, the average obliquity of submarine daylight is likely to vary with depth in a small degree only.

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